eRHIC: ELECTRONS IN THE RHIC TUNNEL

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1 Introduction

Interest continues to grow in the physics of collisions between electrons and heavy ions, and between polarized electrons and polarized protons [1,2,3]. Table 1 lists the primary parameters of the eRHIC design study [4,5]. In the "*ring-ring collisions*" scenario, illustrated in the top of Figure 1, 10 GeV electrons circulate in a third storage ring in the RHIC tunnel. "Pre-polarized" electrons are injected from a full energy linac in the counterclockwise direction at IP4. Collisions are possible with the clockwise rotating ions in the Blue ring at the other five interaction points. In the "*linac-ring collisions*" scenario, sketched in the bottom of Figure 1, the considerable energy which is stored in the electron beam is recovered after a single turn by recirculating the electron beam back through the linac. The accelerating and decelerating electron beams travel in the same direction along the linac in order to avoid collisions.

2 Ring-Ring Collisions

Table 2 shows the ultimate luminosity at the beam-beam limit, given by

$$L \ = \ F_{rev} \, \frac{N_b N_e N_i}{4\pi\sigma^{*2}} \tag{1}$$

where the round beam collision size, σ^*, is assumed to be 0.1 mm, and the number of bunches in each beam, N_b, is taken to be 360 (reasonable) or 2520 (extreme). The single bunch populations for electrons and ions, N_e and N_i, and the average beam currents, I_e and I_i, correspond to beam-beam tune shift parameters of $\xi_e = 0.06$ and $\xi_i = 0.004$. It is not necessarily possible to reach beam-beam limited performance – for example, the electron current of $I_e = 7.7$ A for electron-gold collisions with $N_b = 2520$ bunches may lead to an unacceptable total synchrotron radiation power load, P_{rad}, or an unacceptable linear power load per meter of dipole, P_{lin}.

Table 1: Primary eRHIC parameters

Parameter	Units	Value
Gold top energy per nucleus, E_{Au}	[GeV/u]	100
Proton top energy, E_p	[GeV]	250
Electron energy, E_e	[GeV]	10
Circumference, C	[m]	3833

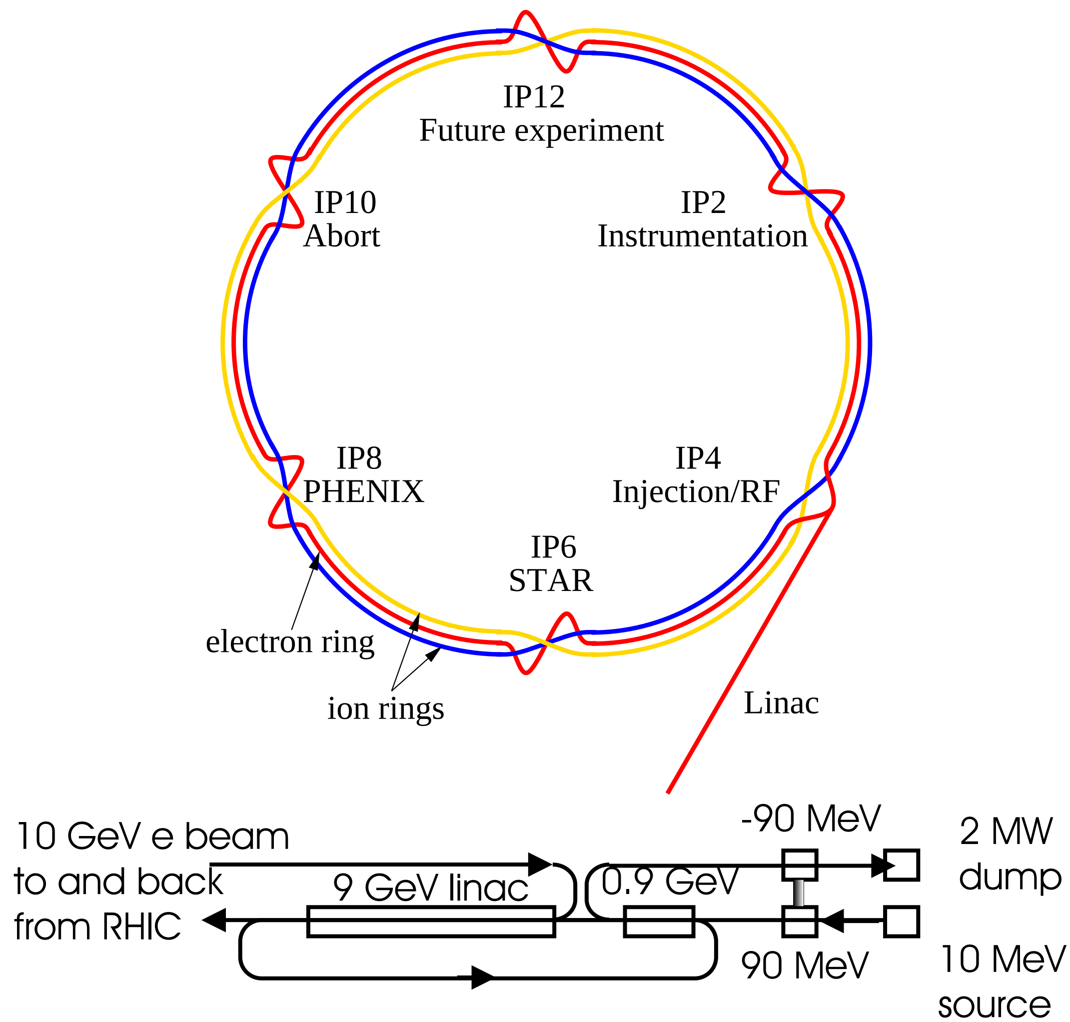

Figure 1: TOP: the injection linac, electron ring, and the two ion rings, in the *ring-ring* collision scenario. BOTTOM: a two stage recirculating linac structure in the *linac-ring* collision scenario.

The eRHIC electron ring has an energy and a circumference strikingly similar to the high energy ring (HER) in the SLAC or KEK B-factory – it has been tellingly observed that *"eRHIC is half a B-factory"* [6,7]. The SLAC HER placed an engineering limit of 10 kW/m on P_{lin}.

The interaction region at IP12 is available for a major new detector, with optics which can be remodeled for optimum compatibility with electron-ion and electron-proton operations. A Yellow ring bypass can be included, allowing electron-hadron collisions at IP12, and simultaneous hadron-hadron collisions at all other interaction regions. Modified beam splitting dipoles could be used as hadron fragment spectrometers, and the triplet cryostats could be relocated.

2.1 Polarization, spin rotation, and synchrotron radiation

The natural Sokolov-Ternov polarization time is 9.9 hours! Thus, the electrons must be injected pre-polarized, for example from a full energy linac equipped with a polarized source. Alternatively, a polarizing booster could be used to accelerate electron bunches from (say) a 1 GeV injection energy to a 10 GeV flat-top. A booster with 1 T dipoles ($\rho = 33.4$ m) and a packing fraction of 0.5 ($C = 420$ m) has a polarization time of only 74 s.

The spin rotators included in the eRHIC straw man optics [4] provide longitudinal polarization at the IP. Unfortunately the high field bends in the spin rotator produce linear power densities

Table 2: Ring-ring performance parameters, at the beam-beam performance limit.

Number of bunches, N_b		360	2520
ELECTRON-GOLD			
Luminosity, L	[$cm^{-2}s^{-1}$]	6.4×10^{30}	$45. \times 10^{30}$
Electron bunch population, N_e		2.43×10^{11}	2.43×10^{11}
Gold bunch population, N_i		1.19×10^{9}	1.19×10^{9}
Electron beam current, I_e	[A]	1.1	7.7
Total radiated power, P_{rad}	[MW]	4.0	27.9
Linear power load, P_{lin}	[kW/m]	2.6	18.3
Gold beam current, I_i	[A]	0.42	2.97
ELECTRON-PROTON			
Luminosity, L	[$cm^{-2}s^{-1}$]	2.1×10^{32}	$15. \times 10^{32}$
Electron bunch population, N_e		1.00×10^{11}	1.00×10^{11}
Proton bunch population, N_i		$.93 \times 10^{11}$	$.93 \times 10^{11}$
Electron beam current, I_e	[A]	0.45	3.16
Total radiated power, P_{rad}	[MW]	1.6	11.5
Linear power load, P_{lin}	[kW/m]	1.1	7.5
Proton beam current, I_i	[A]	0.42	2.92

P_{lin} as large as about 20 kW/m, even for a 1 A average electron beam current. For comparison, note that the electron beam currents at the beam-beam limit in Table 2 vary from a minimum of 0.45 A to a maximum of 7.7 A. Thus, the spin rotator magnets may limit the eRHIC electron current to about 0.5 A. More analysis must be done to see if the power load limits can be increased locally, or if a different approach to the spin rotation is possible, because the high current and high luminosity potential of eRHIC is potentially compromised.

3 Linac-Ring Collisions

The natural advantages of a linac-ring collision scenario are in the ability to vary the electron energy over a wide range without affecting the polarization or beam quality, and in the low electron emittance and energy spread.

In the ring-ring scenario the RF system only makes up for synchrotron radiation power losses. High current electron storage potentially leads to various instabilities and resonances, but the high beam power flux – as high as 77 GW for 7.7 A of 10 GeV electrons – does not need to be replenished on every turn. In the linac-ring scenario, instead of colliding over and over on successive turns, the electrons pass through only one turn before being decelerated in the injection linac to recover their beam energy. The beam is returned at 10 GeV to the entrance of the main linac for deceleration to 1 GeV, and then to 100 MeV in the intermediate energy linac. This observes the Douglas principle of restricting the energy dynamic range to a maximum of 10. Deceleration to 10 MeV follows in a dedicated 90 MeV pre-dump linac.

Table 3 summarizes the parameters of a linac-ring collider with 360 ion bunches. Electron cooling of either gold ions or protons results in smaller ion beam emittances and allows for larger tune shifts in the RHIC ion beam. Other than that, the RHIC parameters are mostly the same as for the ring-ring case, except that the proton bunch population is reduced to 3×10^{10} in order to keep the electron beam-beam tune shift parameter under 1. In the case of gold the limit is set by the beam-beam tune shift for the ions. The large increase in the beam-beam tune shift due to the cooling which may be possible could generate a further increase in the luminosity.

Table 3: Linac-ring collision parameters, assuming electron cooling of RHIC.

Parameter	Units	Value
Electron average current	[A]	0.135
Number of ion bunches, N_b		360
Electron bunch population, N_e		3×10^{10}
ELECTRON-GOLD		
Luminosity, L	[$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	5.6×10^{30}
Gold bunch population, N_i		1.9×10^{9}
Electron beam-beam tune shift ξ_e		0.272
Ion beam-beam tune shift ξ_i		0.0046
ELECTRON-PROTON		
Luminosity, L	[$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	4.6×10^{32}
Proton bunch population, N_i		3×10^{10}
Electron beam-beam tune shift ξ_e		0.688
Ion beam-beam tune shift ξ_i		0.0046

4 Summary

Electron-gold luminosities of the order of 10^{31} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and polarized electron-proton luminosities of the order of 5×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, appear possible. The electron ring total beam current is probably limited to about 4 A by a synchrotron radiation linear power load limit of about 10 kW/m. Spin rotators are optically challenging – with the strongest dipole fields and the highest synchrotron radiation linear power loads, they further limit the electron beam current and the luminosity. The polarization time at 10 GeV is about 10 hours, so the electrons must be injected pre-polarized at full energy, and may not be accelerated through depolarizing resonances. A full energy linac or a polarizing booster can provide full energy pre-polarized electrons. More study is necessary, but eRHIC is feasible.

References

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2. *The first eRHIC workshop*, http://www.star.bnl.gov/afs/rhic/star/doc/www/collab/erhic/erhic.html , BNL, 1999.
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4. *Accelerator Physics issues in eRHIC*, I. Ben-Zvi, J. Kewisch, J. Murphy, S. Peggs, C-A/AP/14, BNL, April 2000.
5. *RHIC Design Manual* http://www.agsrhichome.bnl.gov/NT-share/rhicdm , BNL, 1993.
6. J.B. Murphy, private communication, September 1999.
7. *The Fish License Sketch*, M. Python, London, 1972:
   Is this wretched demi-bee,
   half asleep upon my knee,
   some freak from a menagerie?
   No! It's Eric the half a bee.